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Online Determination of the LHC Luminous Region with the ATLAS High-Level Trigger

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Abstract

During stable-beams operations of the LHC, the ATLAS High Level Trigger (HLT) offers the fastest and most precise online measurement available of the position, size and orientation of the luminous region at the interaction point. Taking advantage of the high rate of triggered events, a dedicated algorithm is executed on the HLT processor farm of several hundred nodes that uses tracks registered in the silicon detectors to reconstruct event vertices. The distribution of these vertices is aggregated across the farm and its shape is extracted through fits every 60 seconds. A correction is applied online to adjust for the intrinsic vertex resolution by examining the apparent separation of split vertices. The location, widths and tilts of the luminosity distribution are fed back to the LHC operators in real time. The transverse luminous centroid mirrors variations in the IP orbit, while its position along the beam axis is sensitive to the relative RF phase of the two beams. The time evolution of the luminous width tracks the emittance growth over the course of a fill. Beginning in 2011, the HLT beam spot measurement also started reconstructing the parameters of each individual filled bunch. This gives rise to a study of single-bunch distributions and opens a window to understanding dynamical features such as beam-beam effects. We describe how the measurement is performed and discuss the results and observations of the luminous region parameters and their time evolution during the high luminosity running in 2011.

Keywords: ATLAS, High-Level Trigger, Primary Vertex, Beam Spot, Beam-beam Interaction

1. Introduction

The Large Hadron Collider (LHC) [1] is a remarkably well instrumented machine. The rapid progress in its operation was made possible by the excellent performance of the beam instrumentation. But despite the wealth of information made available by the accelerator diagnostics, its reach into the LHC interaction regions – which are occupied by its large detectors – is naturally limited. The nearest Beam Position Monitors (BPM) are located at approximately 21.5 m up- and downstream of the ATLAS [2] interaction point (IP1). They measure beam positions with two analogue channels each that achieve an overall accuracy and stability

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in terms of position at the IP in the range of few ten microns on a nominal bunch, limited by non-linearities in the bunch-by-bunch mode. In contrast, the ATLAS Pixel detector comprises over 80 million channels of silicon readout, capable of reconstructing individual tracks that emanate from the interaction region with considerably higher resolution. Through the reconstruction of large samples of event vertices formed by these tracks, the position, size and orientation of the luminous region (also referred to as the "beam spot") can be determined with sub-micron precision. These techniques have been used successfully in the past to characterize the luminous region in ATLAS since the early stages of commissioning during the 900 GeV and early 7 TeV running [3, 4].

The data presented in this note show how these measurements were developed into a full feedback system of the LHC luminous region properties into the ATLAS data acquisition itself. Two characteristics, short latencies (*i.e.* a quasi real-time feedback) and data rates that lead to the highest available statistical precision, make the ATLAS High Level Trigger ideally suited for these types of measurements. In particular, measurements on invididual colliding bunch pairs and their time evolution are in practice only feasible online, where one can exploit the high rate of collision events that are eventually rejected from the data logging. At the same time, the particular environment of the Trigger imposes very tight constraints on computational and network resources, and special alogrithms have to be employed to meet that demanding environment. A continuing challenge (but also an opportunity) arises from the presence of extra collisions in a single bunch crossing (or "pile-up") that are incurred by large bunch-by-bunch luminosities. At the time of this writing, pile-up has reached peak levels exceeding 30 interactions per crossing, and continues to increase. This puts an extra computational burden on the HLT tracking, but at the same time creates possibilities to perform the vertex measurement multiple times per event.

We begin this note by describing the online reconstruction of event vertices and the extraction of the luminous region information from them. We then explain how a vertex splitting method is used to correct for the intrinsic resolution of the measurement. Next we look at the time evolution of the luminous region parameters. We then describe the live feedback for the LHC monitoring and into the HLT itself. And in the final section we take a look at the bunch-by-bunch measurements that are performed by this system and the information it can provide about the machine.

2. Primary Vertex Reconstruction

At the heart of this method is the reconstruction of event vertices formed by charged tracks that emanate from the proton-proton collisions. The two ATLAS sub-detectors used for this are silicon devices: the Pixel detector and the Semi-Conductor Tracker (SCT).

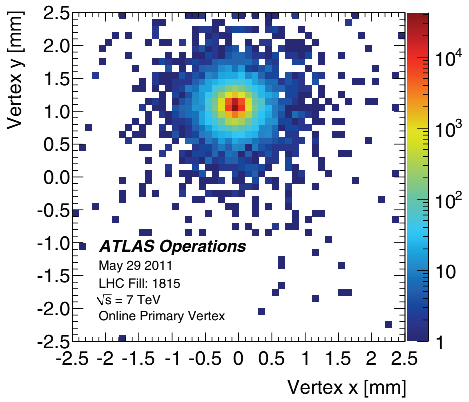
2.1. ATLAS silicon trackers

The Pixel detector, with three barrel layers and three endcap discs on each side, has an excellent hit resolution of $\sigma_{r\phi} \approx 10\,\mu$m in the plane transverse to the beam axis, and $\sigma_z \approx 115\,\mu$m in the direction of the beams.[2] The SCT, which surrounds the Pixel detector and consists of four barrel layers and nine disks on each side of silicon strips, provides resolutions of $\sigma_{r\phi} \approx 17\,\mu$m and $\sigma_z \approx 580\,\mu$m. Both detectors are used in the HLT for pattern recognition, track finding and fitting, with the final vertex resolution being dominated by the Pixel hits. They cover an acceptance range of $|\eta| < 2.5$ in pseudo-rapidity, or a little closer than 10 degrees from the beam axis.

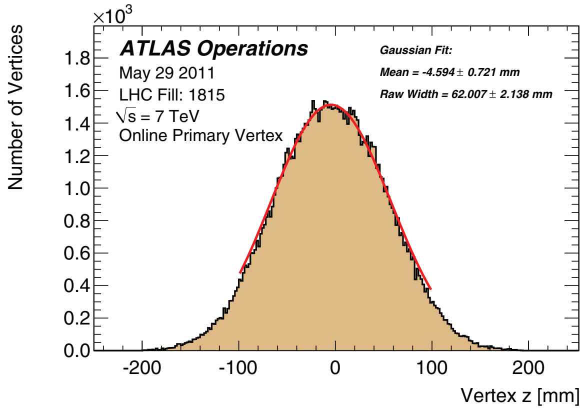
2.2. Beam spot algorithm

Since the typical luminous region is more than 1000 times longer than it is wide – while the vertex resolutions in the two directions are rather comparable – the best handle by far for separating tracks that belong to different pile-up vertices are their impact parameters along the z-axis. Moreover, the hard scattering vertices are characterized by the large transverse momentum (p_{T}) of their leading particles. To exploit this

[2]The ATLAS coordinate system has its origin in the center of the detector, with the x-axis pointing to the center of the LHC, the y-axis pointing up, and the z-axis pointing along the outgoing beam 2 (which runs counter-clockwise around the ring).



(a) Transverse vertex distribution



(b) Longitudinal vertex distribution

Fig. 1. The distribution of primary vertices reconstructed online in the High Level Trigger. The distributions correspond to one minute of data taking and contain well over 100 000 vertices.

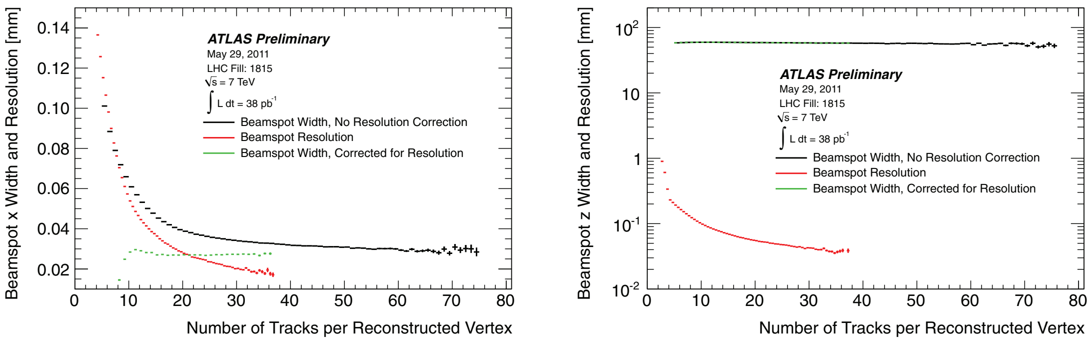
fact, high quality tracks are first sorted in transverse momentum p_{T}, and clusters are formed along z around seed tracks with the highest p_{T}. The track clustering starts with the z_0 impact parameter of the seed track and adds further tracks that fall within a predefined window around that location. With every added track, a new z_0 is computed as the (running) weighted average, taking the track parameter errors into account. This proceeds going down in p_{T} until no further track is found within the window. The method continues with the remaining highest-p_{T} track as the next seed for a new cluster, and so forth. The so-found track clusters are then fed into a fast primary vertex fitter [5] that employs a decorrelating measurement transformation, which greatly reduces its computation time. The vertex fitter in turn performs iterations on the reconstructed vertex while dropping tracks whose χ^2 contributions exceed a predefined limit. The resulting vertices are subjected to additional quality cuts and the final positions are used for the vertex distributions.

2.3. *ATLAS High Level Trigger*

The first stage of the ATLAS DAQ system [6] that has access to the silicon data is the second level (L2) Trigger, which is part of the two-tiered High Level Trigger (HLT) [7] that also includes the subsequent Event Filter. The L2 Trigger operates on the output of the L1 hardware trigger, comprising a large number of separate trigger algorithms that run at combined input rates of up to 75 kHz. To achieve such rates, the HLT algorithms are executed on a massively parallel farm of over a 1000 multi-core nodes. For the data described here, 10 racks of 30 dual quad-core nodes were dedicated to the L2 Trigger, amounting to 2400 independent processes. While the Event Filter can process fully built events at around 5 kHz, the higher L2 rates are made possible through algorithms that reconstruct events only partially, based on so-called Regions-of-Interest (ROIs) built from the L1 decision. At present conditions, the two silicon detectors make up only a small fraction (~80 kB) of the full ATLAS event size (~1.6 MB), which makes it feasible to process and log their data at comparatively high rates. However, as opposed to the typical L2 algorithm, the beam spot algorithm does not operate on ROIs but rather employs a "full-scan" of the detector, *i.e.* reading all of its hits, which makes fast track finding especially important. At this point, the full-scan tracking that is invoked by the beam spot algorithm is dominating the CPU time spent on the L2 farm, and work is ongoing to keep its resource use within limits.

2.4. *Vertex distributions*

Projections of the three-dimensional spatial distribution of reconstructed primary vertices are histogrammed and published every 60 seconds. These histograms are then aggregated ("gathered") accross the farm, first at the rack level then at the top level, and republished onto the ATLAS online network. The large amount of statistics in the aggregated histograms gives rise to very precise determinations of all luminous



(a) Transverse resolution (for the example of the horizontal (x) axis)

(b) Longitudial (z) resolution.

Fig. 2. The observed width of the primary vertex distribution, the measured resolution, and the resolution-corrected width, all as a function of the number of tracks per vertex. In the transverse plane (a), the observed width decreases with the track multiplicity as the resolution improves, while the corrected width stays essentially flat. The z resolution (b) has a similar dependence on the number of tracks as the resolution in the transverse plane. However, in contrast to the transverse plane, the longitudinal resolution correction is entirely negligible.

region parameters. In addition, the rate of reconstructed primary vertices can be used as a measure of luminosity as described in [3], although with today's pile-up levels this has become increasingly difficult and is currently being reexamined. The transverse distribution of reconstructed primary vertices, for 100k vertices registered by the HLT in just one minute of data taking, is shown in Fig. 1. It is visible by eye that the collision point is offset with respect to the center of the ATLAS detector by about 1.1 mm vertically, and, less visible in this plot, by about $-50\,\mu$m horizontally. This information is vital for the trigger as explained in the following sections.

3. Online Resolution Correction

In order to retrieve the luminous sizes from the widths of the observed vertex distributions, those widths have to be corrected for the intrinsic resolution of the vertex reconstruction. This resolution correction is essential in the transverse plane, where the typical per-vertex uncertainty is on the same order, or larger, than the size of the beams. Actual luminous widths are therefore significantly smaller than the observed ones. (This effect is entirely negligible in the longitudinal direction, where the luminous length is orders of magnitudes above the resolution.)

A number of factors contribute to the effective vertex resolution, ranging from the detector conditions to the event composition at the current trigger settings. Moreover, these factors can vary from one data-taking run to the next, which is why it is essential to determine them online. The event composition in particular has to adjust to an ever evolving Trigger menu. Just as the luminous region parameters themselves, the resolution correction demands the large statistics that is only available in the aggregate distributions from all trigger nodes. Therefore, event distributions have to be produced on all nodes simultaneously such that from their sum the correction can be derived.

The method chosen for estimating the resolution is to split each vertex in two halves, which can then be fitted again separately, and to record their apparent separation in three dimensions. This also plays to the fact that the effective vertex resultion is a strong function of the number of tracks on the vertex, with the resolution improving the more tracks emanate from the vertex. To avoid systematic biases, the tracks associated with a given vertex are first re-sorted in azimuth (ϕ), which bears virtually no correlation with how well they are measured. Then the group of tracks is split into two samples – as one, two, one, two etc. – and the resulting track lists are re-fitted using the same algorithm as described above. In this way, each original vertex contributes to derive the resolution for a vertex with half the number of tracks, estimated as $\frac{1}{\sqrt{2}}$ times the separation of the daughter vertices. (Only resulting vertex pairs with the same number of tracks are used for this calculation, while the even-odd combinations are merely monitored as interpolations between the others.)

Distributions of the split-vertex separation are recorded along with the vertex distributions in bins of track multiplicity. Gaussian fits are performed to each multiplicity bin to extract observed widths and estimated resolutions, respectively. Fig. 2 shows the observed width of the primary vertex distribution as a function of the number of tracks in the vertex. In addition, the estimated resolution is shown as well as the resulting width after subtracting that resolution in quadrature in each multiplicity bin. As expected, the resulting true width stays flat over a range of different resolutions. Fig. 2(a) shows the horizontal resolution as an example, with the vertical looking very similar. The corrected luminous size is extracted from fitting a constant to that plateau. For comparison, the longitudinal width and resolution are shown in Fig. 2(b). The longitudinal resolution is only about a factor of two worse than the transverse one, and therefore completely negligible given the much larger luminous length. The method was found to produce stable results down to a certain multiplicity and starts to fail when the resolution becomes worse than approximately twice the true width. The same behavior was observed for fills with larger beam sizes.

It should be noted that the data presented here still suffer from systematic effects that limit the accuracy of the width measurement to the level of a few percent and are being actively addressed. These lead to biases that are most pronounced at the beginning of each data-taking run when the resolution correction is still low on statistics. As explained above, the split vertex method is limited by the need for a corresponding sample of events with twice as many tracks per vertex. Therefore, an increasing demand is put on a sufficient rate of very-high multiplicity vertices in order to resolve the smaller beam sizes expected in the future with smaller transverse emittances and the further squeezing of β^*.

4. Time Evolution of the Luminous Region

Using the one-minute sampling described above, combined with the precision afforded by the high event rates, one can retrieve time evolutions of all luminous region parameters.

4.1. Time-variation of the centroid position

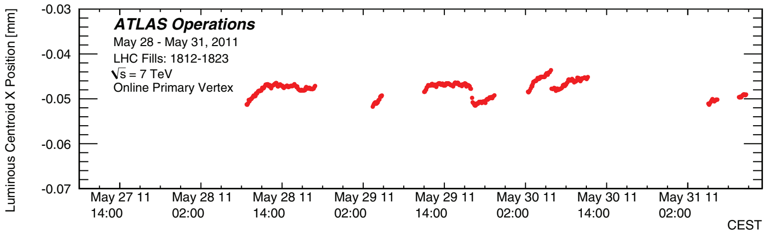
The most straight-forward to track are the positions of the luminous centroid, which mirror IP-orbit changes (in the transverse plane) and RF-phase changes (longitudinally). Fig. 3 shows that the centroid position does not stay constant during a fill but rather varies as a result of orbit corrections. These variations around the average are small enough not to matter for HLT tracking and most triggers, but they do have a very sensitive effect on triggers that make use of impact parameter or decay length properties, such as *b*-jet tagging, as will be discussed in section 5.

4.2. Time evolution of the luminous sizes

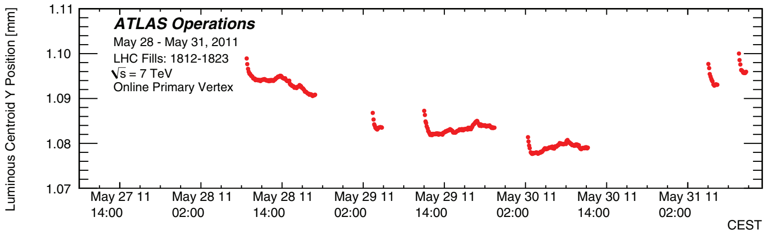
The change in the luminous sizes follows a more predictable pattern. Fig. 4 shows the evolution of the sizes as a function of time for six separate fills recorded over the span of four days. One can very clearly see the effect of the beam emittance blow-up that takes place during each fill. This effect results in a growth of the luminous sizes, over the course of a 10 hour fill, of approximately 15 % and 10 % in the horizontal and vertical planes, respectively. The increased transverse luminous sizes are directly connected to a corresponding drop in specific luminosity during the fill. Likewise, the longitudinal emittance shows a growth of similar rate. It can further be seen from the plots that fill-to-fill variations are comparatively small, but not negligible.

5. Feedback System

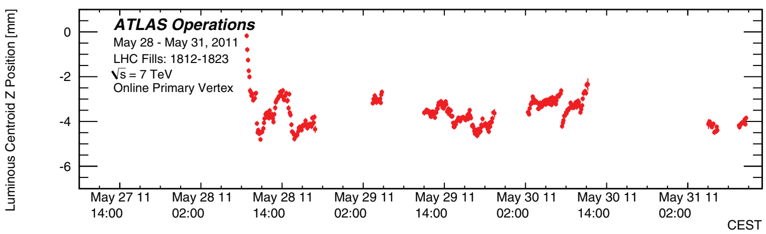
Following the steps described in the previous sections, information about the luminous region parameters is distributed to a number of places.



(a) horizontal (x)



(b) vertical (y)



(c) longitudinal (z)

Fig. 3. Time-variation of the luminous centroid position in x, y, and z measured in the High Level Trigger every five minutes, for six separate LHC fills recorded over the span of four days.

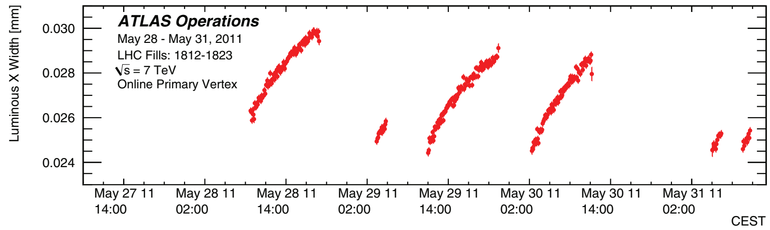
First, live histograms from the one-minute samples are published and made available in the ATLAS control room and over the Web. These provide details on the data quality, as well as serving as an early monitor for potential problems with triggering, tracking or vertex reconstruction.

From these distributions, the luminous region parameters are extracted through fits also once a minute, including the online resolution correction.. All samples are stored in the conditions database for direct or later retrieval. The luminous region parameters are also transmitted to the CERN Control Center (CCC), where they are visible for instance on this page [8]. They are stored in the LHC Logging Database where they can be correlated with other beam instrumentation variables.

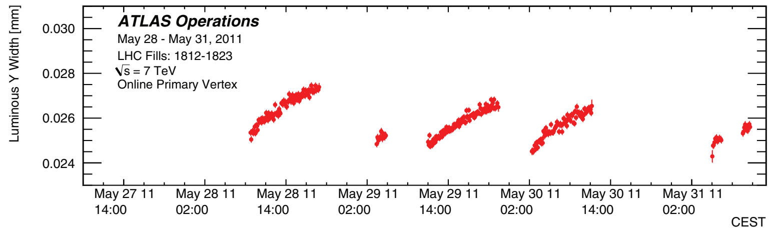
5.1. Parameter redistribution

As introduced in Sec. 4, time variations of the centroid position, caused by IP-orbit and RF-phase changes, as well as the continuous growth in luminous sizes over the course of a fill, make it necessary to update parameters used by the HLT *during* data taking. This includes a bootstrap phase at the beginning of each fill, in which the most sensitive triggers, *i.e.* the already mentioned b-tagging, are held off until a reliable beam spot has been determined. An example for how a shifted beam spot can fake large track impact parameters so they resemble those from b-jets can be found in [9], which illustrates the need for automatic updates.

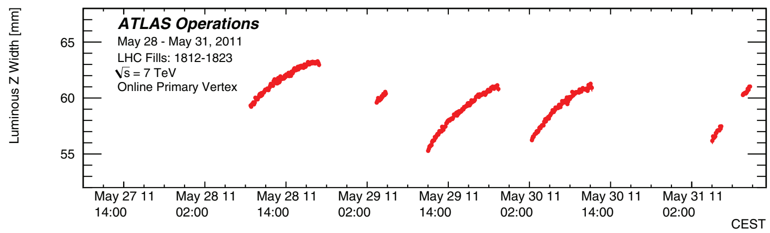
A major challenge with this is to transmit the parameters back to the thousands of HLT processors – which process the event stream at many kHz – on a sharp time-boundary and without incurring deadtime. What makes this possible is a specifically designed database infrastructure for configurations that is comprised of a special server, called the CORAL Server, and a set of caching and multiplexing proxies. The



(a) horizontal (x)



(b) vertical (y)



(c) longitudinal (z)

Fig. 4. Time-evolution of the luminous size in x, y, and z measured in the High Level Trigger every five minutes, for six separate LHC fills recorded over the span of four days. The effect of the transverse emittance blow-up is clearly visible during each fill and is on the order of 15 % on the horizontal width and 10 % on the vertical width for a 10 hour fill. Similarly, the luminous length increase from longitudinal emittance blow-up is on the order of 10 % for a 10 hour long fill.

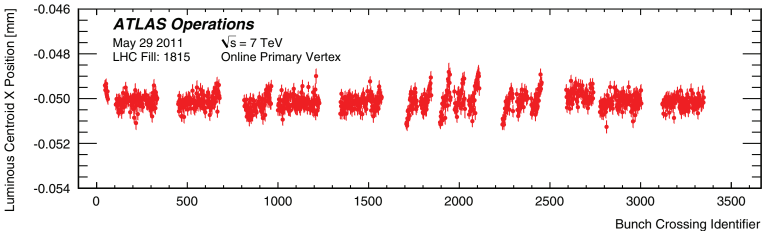
proxies are arranged in a hierarchical structure that mirrors the segmentation of the hardware into nodes and racks. More about this system can be found in [10]. With the help of the CORAL proxies, the HLT clients can retrieve a new set of beam spot parameters from the Conditions Database in an average time of just a few milliseconds – fast enough not to exceed the average processing time of around 40 ms in L2 (and negligible in the Event Filter).

The second part is to signal the nodes about the pending updates. The only viable path for this, that is both reliable and without latency, is the DAQ event path. Therefore, a dedicated field has been created in the data fragment of the Central Trigger Processor that carries this information when the luminosity block number is incremented and sends it to the node along with the triggered event. This is activated whenever a command to update is injected into the CTP.

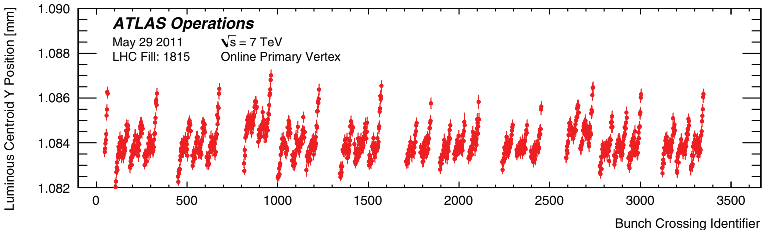
5.2. Automatic Trigger updates

To keep the configured beam spot current, three independent criteria are used, based on the observed centroid position, the luminous widths and their respective errors, that can each trigger an update:

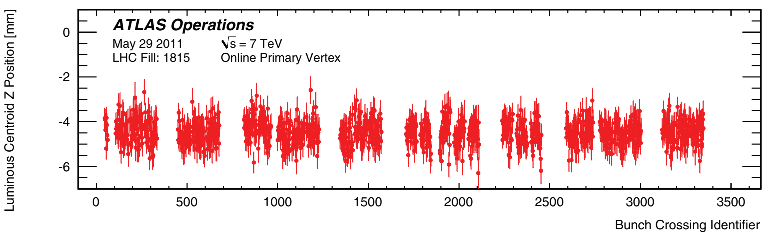
- a change in the position in one direction of 10 % or more of the corresponding width, with a 2 sigma significance;
- a change in either of the widths from the last stored value of 10 % or more, with a 2 sigma significance;



(a) horizontal (x)



(b) vertical (y)



(c) longitudinal (z)

Fig. 5. The luminous centroid position in x, y, and z measured in the High Level Trigger for each colliding bunch pair separately. Distinct structures are visible, in particular in the vertical position of the interaction-point, with variations of up to 5 μm and repeating patterns across the injected bunch trains.

- a reduction in any of the errors of 50 % or more.

With these criteria, updates of the nominal HLT beam spot are performed several times during a typical run: with a few updates at the beginning that settle on a high-precision determination, and then a few more over the course of the fill to adjust to any actual changes in the machine.

6. Measurements on Individual Bunch Pairs

A capability that is more or less unique to the L2 Trigger is the measurement of the luminous region for individual colliding bunch pairs. This is made possible by the large number of usable events in the Trigger that would not be possible to keep for offline analysis. The filling schemes at 50 ns bunch spacing contain a maximum of 1380 bunches, with typically 1331 of them colliding in ATLAS (and CMS).

Fig. 5 shows the luminous centroid position as a function of the (sequential) bunch crossing identifier (BCID). While the centroid position in the horizontal (separation) plane is mostly contained within $\pm 1\,\mu$m of its average, that in the vertical (crossing) plane exhibits distinct structures in each bunch train that repeat along the beam. This is the first time this behavior, which was expected based on simulations, has been observed experimentally at the LHC, and studies show that it can be attributed to beam-beam effects arising from long-range interactions [11, 12]. These long-range interactions occur as incoming bunches within a train – before they reach the interaction point – interact with outgoing bunches from the colliding train, in such a way that the bunches exert a force (kick) on each other that ever so slightly changes their orbit. The amplitude of the orbit distortion depends on the emittance, the IP β-function, the crossing angle, and finally the number of the long range encounters experienced by each bunch. That number is fairly constant in the core of the train, but smaller at the head or tail. This is because bunches near the head of the train see fewer outgoing bunches before they collide and bunches near the tail see fewer incoming bunches after they have collided. For the same reason is the number of long range interactions smaller near the larger bunch gaps than near the smaller ones, as can be seen in the plot.

Lastly, the data present a hint that the group of bunch trains around BCID 2000, and perhaps the two neighboring ones, may exhibit less of a beam-beam effect in the vertical plane, and instead a non-zero one in the horizontal plane. This is intriguing behavior that is not yet understood and topic of further investigation.

The data shown here represent the average over an entire fill. To allow one to see time evolutions, and to be less affected by variations during the fill, the per bunch measurements are also performed every 20 minutes. This still provides sufficient statistics to achieve a 5 % statistical error for each bunch pair.

7. Conclusions

The ATLAS High Level Trigger is the first system able to see tracks and vertices, and to allow a reconstruction of the ATLAS luminous region. High event rates make this both extremely challenging and precise. The ability to use (mostly) rejected events is unique to the HLT and is exploited in the data presented here. A method to correct for resolution effects based on vertex splitting has been put in place and that produces consistent results down to current spot sizes around 20 μm. The data presented still suffer, at this time, from systematic biases that limit the accuracy of those corrections to the level of a few percent, primarily at the beginning of a data-taking run. Timelines of luminous region parameters are produced online that provide measurements of IP-orbit and RF-phase variations as well as emittance growth.

The early online beam-spot measurements have developed into a complex feedback system that not only transmits live parameters to the LHC operators, but also performs automatic updates of the parameters used by the HLT farm itself. Owing to the high rate of events, the system is able to perform bunch-by-bunch measurements of the currently more than 1300 colliding bunches down to the sub-micron level. These ATLAS measurements at the IP are complementary to, or of higher precision than what is achievable with the LHC beam instrumentation. This has already led to some interesting observations *e.g.* of beam-beam effects that were shown here for the first time at the LHC, and are the topic of ongoing research.

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